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Gear Noise, Vibration, and Diagnostic Studies at NASA Lewis Research Center

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GEAR NOISE, VIBRATION, AND DIAGNOSTIC STUDIES AT NASA LEWIS RESEARCH CENTER

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SYNOPSIS The NASA Lewis Research Center and the U.S. Army Aviation Systems Command are involved in a joint research program to advance the technology of rotorcraft transmissions. This program consists of analytical as well as experimental efforts to achieve the overall goals of reducing weight, noise, and vibration, while increasing life and reliability. This paper highlights recent analytical activities in the areas of gear noise, vibration, and diagnostics performed in-house and through NASA and U.S. Army sponsored grants and contracts. These activities include studies of gear tooth profiles to reduce transmission error and vibration as well as gear housing and rotordynamic modeling to reduce structural vibration transmission and noise radiation, and basic research into current gear failure diagnostic methodologies. Results of these activities are presented along with an overview of near term research plans in the gear noise, vibration, and diagnostics area.

1 INTRODUCTION

Future military and civilian helicopter applications demand more powerful, lighter, and quieter rotorcraft. Advancing the technology of rotorcraft transmissions is a crucial part of meeting the operational and mission requirements of future helicopters. A joint helicopter transmission research program was established between the NASA Lewis Research Center and the U.S. Army Aviation Systems Command in 1970 to perform advanced transmission studies for future rotorcraft. The major goals of the program are to increase the life, reliability, and maintainability, reduce the weight, noise, and vibration, and maintain the relatively high mechanical efficiency of the gear train in helicopter transmissions. To achieve these goals, analytical and experimental studies are being performed in a variety of areas including advanced materials and lubrication schemes, kinematics and dynamics of gears and gear train systems, and gear fault diagnostics (1,2). These studies are performed in-house and through NASA-ARMY sponsored research grants and contracts with U.S. universities and industry.

This paper reviews results of recent analytical activities at NASA Lewis in the areas of gear noise, vibration, and diagnostics. The research projects are grouped and presented in four major categories. These are: 1) gear tooth profile research, 2) gear train dynamics research, 3) gear housing dynamics, transmissibility, and acoustics research, and 4) gear diagnostics research. Some near term research plans are also presented along with some limited experimental results.

2 NASA LEWIS GEAR NOISE, VIBRATION, AND DIAGNOSTICS RESEARCH

The gear dynamics research activities at NASA Lewis focus on developing advanced technologies and analytical tools to help achieve the goals

of reduced weight, vibration, and noise in future rotorcraft transmissions. These studies usually involve numerical analysis of a transmission system or component using computer modeling techniques. The models become research tools and eventually design tools after they are verified by experiment.

Results of recent activities at NASA Lewis in the areas of gear tooth profile research, gear train dynamics research, gear housing dynamics, transmissibility, and acoustics research, and gear diagnostics research are presented below.

2.1 Gear tooth profile research

Transmission error in gearing is the prime contributor to gear related noise and vibration. The transmission error is defined to be the angular deviation of the output gear rotation as compared to the input gear due to manufacturing errors and elastic deflections of the gear teeth. Two research activities at NASA Lewis have focused on ways to reduce the transmission error through gear tooth profile modification studies.

The first study examined the effects of gear tooth crowning to reduce the transmission error due to gear misalignments (3,4). Spur gears are known to be very sensitive to misalignment. Misalignment between spur gears in mesh will cause the tooth bearing contact to shift toward the edge of the gear tooth surfaces and cause transmission error and possible damaging overloads. Previous crowning methods were primarily concerned with improving the bearing contact of misaligned gears (i.e., avoiding edge contact), with no consideration for reducing transmission error. The new method determines the optimum geometry of a crowned pinion tooth surface to reduce the sensitivity of the gears to misalignment, locate the bearing contact, and minimize both the magnitude and variation in the magnitude of the transmission error.

This method, for optimum geometry of the crowned pinion tooth surface, is based on a number of considerations. Misaligned spur gears with a crowned pinion tooth surface can provide two types of transmission errors, as shown in Fig 1(a) and 1(b) from Ref 3. The first type of transmission error, similar to a repeating ramp function, appears in Fig 1(a). This is not acceptable because the curve has discontinuities where the load is transferred between tooth pairs. The discontinuity causes a jump in angular velocity which results in an increase in the vibration and noise level of the mesh. The second type of transmission error (Fig 1(b)), looks like a parabolic function. This is more acceptable because the tooth meshing is continuous. Discontinuities in the transmission error curves are avoided, allowing a smoother transition when the load transfers to the next pair of teeth. To assure the parabolic transmission error shape, the pinion surface crowning is developed using a special tool during manufacture. This tool creates a pinion surface geometry whose axial section deviates slightly from an involute curve. No modification is required for the teeth of the mating gear which remain true involute surfaces. Results of several case studies (3,4) show that this method minimizes the sensitivity of a set of gears to misalignment. Similar methods can be applied to helical and spiral bevel gears.

The second study analyzed the effects of a number of different linear and parabolic tooth profile modifications on the transmission errors and dynamic loads of a set of parallel axis spur gears (5,6). The study used the computer program DANST (Dynamic ANALYSIS of Spur gear Transmissions), which was developed to analyze the effects of peripheral masses and shafts, and tooth profile modifications and deviations on the dynamic tooth loads of a set of spur gears in mesh (7,8,9). Applying tip or root relief to the teeth on a set of spur gears is a widely used practice to reduce dynamic loads. Because of this, a more thorough understanding is needed on how the size and shape of a profile modification can effect the dynamic characteristics of a spur gear system.

Various profile modifications and input conditions were used to study the effects of these variables on the dynamic load. Linear profile modification is defined on a tooth profile modification chart by a straight line which represents the deviation of the tooth surface from a true involute shape. Likewise, parabolic profile modification is represented by a parabolic curve on the tooth profile modification chart. The baseline linear profile modification used in this study starts at the highest point of single tooth contact and ends at the tooth tip. The magnitude of the baseline modification is equal to the gear tooth deflection at the tooth tip due to tooth loading at the highest point of single tooth contact. Half of the required modification is applied to each of the mating gears. The baseline parabolic modification used in this study starts with the parabolic modification curve tangent to the normal profile at the highest point of single tooth contact and ends at the tooth tip. In this work, the same values for the magnitude of modification (the amount at the tooth tip) were used for both linear and parabolic modification.

Also, tooth spacing errors were neglected in this study. A matrix of computer runs were performed in which the length of modification, magnitude of modification, speed, and load were varied for both the linear and parabolic modification shapes.

Results of this study indicate that both the amount and type of tooth profile modification have a significant effect on the dynamic performance of a spur gear system. Fig 2 from Ref 6 compares linear (Fig 2(a)) and parabolic (Fig 2(b)) modification shapes. In Fig 2 the amount of tooth modification is defined such that the baseline modification amount is unity. The dynamic load factor is defined as the ratio of the maximum dynamic tooth load during meshing to the static tooth load. Gears with parabolic profile modification were found to be less sensitive to changes in applied load, amount of modification and length of modification than gears with linear profile modifications. It was also found that gears with parabolic modification require a slightly longer length of the modification zone than gears with linear modification to achieve minimum dynamic loads. The results also indicate that the length of modification has a greater effect on dynamic response for both linear and parabolic modifications than does the magnitude of modification. For gears that operate at a nearly constant load (design load to moderate overload) results show that linear profile modification is the optimum way to reduce dynamic tooth load. However, for gears which must operate over a wide range of loading, it was found that parabolic tooth profile modification is superior for minimum dynamic response.

Current research efforts at NASA Lewis include efforts to validate program DANST by comparing the results with experimental data from the gear noise test rig. DANST is also being extended to provide dynamic analysis of high contact ratio spur gears.

2.2 Gear train dynamics research

Vibration in rotorcraft transmissions is a result of a complex interaction between the various gears in mesh and also the dynamic properties of the bearings, shafts, and masses in the system. Vibration is a critical factor in newer transmission designs because high power to weight requirements result in lighter and more flexible transmission components. To reduce development costs and time, the transmission designer must be able to accurately predict vibration and its effect on future rotorcraft transmissions. Over the past two years, several dynamic gear system computer programs have been developed and refined at NASA Lewis. These programs were developed to provide an understanding of the dynamic relationships between the various components in a transmission system, and to eventually serve as design tools for industry.

The research reported in Ref 10 expanded an existing single stage epicyclic gear dynamics program, GRDYNMULT, to allow analysis of two stage epicyclic transmissions with peripheral components. The original GRDYNMULT program is capable of modeling a single mesh

gear system, or planetary, star, and differential systems with up to 20 planets. It calculates several parameters including dynamic mesh loads, tooth root stresses, hertz stresses, and flash temperatures. Options such as a floating sun gear, a flexible ring gear or planet carrier, and tooth spacing errors can be included in the program model. The upgraded program GRDYNMULT can analyze a two stage transmission in which either stage can be a single mesh, planetary, star, or differential system. The two stage system includes an input mass and shaft, an output mass and shaft, and a connecting shaft. The shafts are each modeled as torsional springs and dampers.

The current single stage version of GRDYNMULT has been compared with experimental test data from a UH-60A Black Hawk helicopter transmission tested in the 2240 kW (3000 Hp) transmission test stand at NASA Lewis. Overall results of this study indicate good correlation between the actual dynamic behavior of the transmission and the predictions based on computer simulation (11). Similarly, the two stage version of GRDYNMULT will be verified by comparing it with data from the planetary gear test rig at NASA Lewis. This test rig has two OH-58A Kiowa planetary assemblies mounted back-to-back in a regenerating torque loop configuration. This test stand is used primarily to study performance characteristics of planetary gear assemblies.

Another study resulted in the development of a finite element model of a geared rotor system with flexible bearings (12). The computer program of this model considers the transverse and torsional vibration of the shafts, and the transverse vibration of the bearings in the analysis. The model includes rotary inertia of shaft elements, flexibility and damping of the bearings, material damping and axial loading of the shafts, and the coupling between the torsional and transverse vibration of the gears. To model the dynamics of the gear mesh, the program uses a constant mesh stiffness coupled with a displacement excitation function. This function represents the static transmission error of the gears in mesh. The program is capable of calculating the natural frequencies, corresponding mode shapes, and the dynamic loads at various positions in the system when excited by mass imbalance, geometric eccentricities, and transmission error.

A study was performed using this geared rotor dynamic program to determine the effect of bearing flexibility on the dynamics of the system (12). It was found that when bearing stiffness values were decreased below a critical value the system natural frequency corresponding to the gear mesh decreases significantly. With compliant shafts, there is no significant change in the system natural frequency corresponding to the gear mesh when bearing stiffnesses were increased beyond a limiting value. It was also found that the gear tooth dynamic loads and shaft deflections in the torsional and transverse directions decrease as bearing compliance is increased.

Near term plans include validating the geared rotor dynamic model by comparing predictions of the program with experimental data

from the gear noise test rig at NASA Lewis. The gear noise rig has strain gages at the gear teeth and accelerometers at the bearings to provide data under a variety of conditions for program verification.

2.3 Gear housing dynamics, transmissibility and acoustics research

The reduction of cabin noise levels will be increasingly important for future rotorcraft designs. Reducing cabin noise levels will reduce pilot fatigue and aid in communications between crew and ground stations. A major source of cabin noise in rotorcraft is gear mesh induced vibration structurally transmitted to the cabin. An understanding of the complex transmission paths and the related interaction between the gear mesh and housing dynamics is a crucial step in the overall plan of reducing vibration and noise in rotorcraft transmissions. Several research activities at NASA Lewis have focused on modeling the dynamics, transmissibilities, and acoustics of a simple transmission housing. These efforts are supported by experimental data from the gear noise rig. This rig was specifically designed to study methods for reducing gear induced vibration and noise in structures. A summary of these efforts along with some results are presented below.

One study analyzed the dynamics of the gear housing from the gear noise rig using both finite element analysis and experimental modal analysis (13). The gear noise rig gearbox has a rectangular shaped housing made of 0.006 m (0.25 in) thick SAE 1020 steel plates welded together. The analysis was conducted on the housing without the rotating components (gears, shafts and bearings). Both rigid and flexible mounts were studied. The rigid mount reflects the actual condition of the test gear housing, and the flexible mount simulates the mounting condition on a rotorcraft. The effect of gear housing stiffeners was also evaluated. Experimental modal analysis was conducted on the actual gear housing at NASA Lewis to validate the analytical model.

Results show that for the particular gear housing studied the flexibility of the mount has more influence on housing dynamics than the addition of housing plate stiffeners. The flexibility of the gear housing mount was found to directly influence the type and frequencies of the primary housing modes. In the rigidly mounted case the primary modes correspond to the elastic plate modes of the housing. In the flexibly mounted gearbox the primary modes occur at frequencies lower than the rigid mount case, with the mode shapes corresponding to rigid body modes of the housing. The housing plate stiffeners did not significantly change the nature of the mode shape predictions. However, the mode shapes of the housing with stiffeners occur at higher frequencies than the corresponding mode shapes of the housing without stiffeners. As seen in Fig 3 (from Ref 13), the finite element model housing mode predictions correlate well with the results of the experimental modal analysis conducted on the actual housing. The finite element model of the housing with rigid mounting conditions and plate stiffeners was used for comparison to the experimental modal data in Fig 3.

Further work concentrated on the complex transmission of vibration through rolling element bearings (14). This study resulted in the development of a new methodology for modeling the transmissibility of vibration through rolling element bearings. Current bearing models either assume ideal boundary conditions for the shafts or treat the bearing as a purely translational stiffness element. These models predict only in-plane casing motion with transverse forces at the shaft; however, experimental results show the casing vibration to be primarily flexural, or out-of-plane (14). The ability to accurately model the transmission path of vibration from connecting shafts, through the bearings and housing to the attached structure is a crucial step in reducing structure borne vibration and noise. A new bearing stiffness model was developed which consists of a stiffness matrix of dimension 6 by 6 with dominant off-diagonal as well as diagonal rotational terms. These terms couple the shaft bending motion to the plate flexural motion. A numerical solution scheme was also developed to estimate the stiffness coefficients of the bearing matrix using the mean bearing load vector.

Results of initial experimental tests show the new bearing model to be superior to previous models in predicting vibration transmitted through rolling element bearings (14). A bearing rig was used for experiments to verify the new model. The rig is capable of measuring acceleration in the plane of the housing as well as perpendicular to the housing (parallel to the shaft). As seen in Fig 4, (from Ref 14) the new bearing model agrees well with the experimental data for both the in-plane (Fig 4(a)) and out of plane (Fig 4(b)) transmitted vibration. As seen in Fig 4(a), the new bearing model gives better correlation with experimental data for in plane vibration transmission than current models. The current bearing models do not predict transmitted vibration in the out-of-plane direction, as evident from Fig 4(b).

Future plans include using this new bearing model to predict the vibration transmitted through the bearings on the housing of the gear noise test rig at NASA Lewis. The gear noise test rig has accelerometers at several bearing locations and both load cells and accelerometers at the housing mounts, specifically for transmissibility studies. Results from the new bearing model will be compared with experimental data at a variety of conditions.

In another study a new method was developed to model the overall dynamics of a multimesh, multistage geared rotor bearing system (15). This method combines the nonlinear gear mesh dynamics with structural lateral and torsional vibration of the system to determine the global system response. The modal method is used to transform the equations of motion into modal coordinates to reduce the degrees of freedom of the system. A computer program was developed based on this method. The program includes the effects of rotor mass imbalance and shaft bow, gyroscopic moments, and variable shaft geometry and bearing support. Recently, the program was revised to include the effects of gear housing vibration in the overall system dynamics.

Future plans include developing a relationship between the acoustic and dynamic characteristics of the system. Again, the gear noise test rig at NASA Lewis will be used to verify the model.

There have been many studies of vibration propagation in geared systems and transmission through elastic structures, but until recently there was little progress towards prediction of actual sound radiation caused by geared transmissions. The acoustic intensity program BEMAP (Boundary Element Method for Acoustic Prediction) was adapted to allow prediction of the sound field of a gearbox. BEMAP (16) applies the boundary element method to predict near and far field acoustic intensity values of a vibrating object. The surface geometry of the object may be fairly complex. Either finite element or experimental modal analysis data may be used as inputs for BEMAP.

A preliminary sound intensity analysis was conducted using experimental mode shape data from the NASA gear noise test rig gearbox. The shape of a vibration mode of the gearbox top and the predicted sound intensity corresponding to this mode are illustrated in Fig 5. For this mode, the gearbox top acts as two small sound sources producing a directional sound field.

Future plans include verifying BEMAP acoustic predictions using a robotic acoustical intensity measurement system capable of performing automatic scans of acoustic intensity over plane and spherical surfaces.

2.4 Gear diagnostic research

In aerospace applications, where weight and size are premiums, gear systems are usually designed to high stress limits. For rotorcraft transmissions this design constraint translates into frequent transmission overhauls. A reliable gear train condition monitoring system is a critical element in the cost efficient operation of current and future rotorcraft. NASA Lewis has recently initiated a research program to study new and existing techniques in gear train diagnostics. Results from the first phase of this program along with some near term plans are discussed below.

The first phase of this program involved investigating and applying current gear failure prediction techniques to experimental data from a gear fatigue test rig (17). The analytical and experimental work was performed in-house at NASA Lewis. Spur gear fatigue test rigs are used at NASA Lewis to obtain crucial data on the effects of gear materials, gear surface treatments, lubricants, and lubrication methods on the fatigue strength of aircraft quality gears. Diagnostic research data was obtained by periodically recording the vibration signals from the test rig as gears were run to failure. A one pulse per revolution signal was recorded for time averaging operations. eleven gear runs were recorded representing four major failure modes. These were: 1) heavy tooth surface wear; 2) tooth breakage; 3) single pits on teeth; and 4) distributed pitting on teeth. Current diagnostic techniques were applied to

this data to evaluate their effectiveness for detecting these failure modes. Among the diagnostic methods investigated were the FMO and FM4 techniques developed by Stewart (18), and the time signal demodulation technique proposed by McFadden (19).

The prediction methods were able to detect gear failures involving heavy wear or distributed pitting but fatigue cracks and single large pits were not detected. The FMO parameter and the standard deviation of the difference signal from FM4 reliably detected heavy wear. Figure 6 illustrates the response of the FMO parameter for a gear with heavy wear. These results support the theory that as a gear wears the vibration energy redistributes from meshing harmonics to sidebands. None of the methods predicted tooth failure due to fatigue cracks, which resulted in tooth breakage in two of the cases. It is suspected that the fatigue cracks were not detected because of long intervals between data acquisition windows rather than in the methodology. No method detected single pit failures even though some were relatively large compared to tooth size. Distributed pitting damage was detected by the FMO parameter. It is theorized that the pitting occurred over enough of the teeth to act as a uniform wear phenomenon.

Close inspection of the data showed that the frequency response between the gear shaft and the transducer significantly affects the vibration signal. Frequency response measurements taken between the gear shaft and the transducer revealed the unidentified peaks found in the spectrum to be related to the natural frequencies of the housing. These nongear mesh, resonance-related peaks were, in most cases, greater in magnitude than the gear mesh related peaks. Because of this, the resonant frequencies of the housing were filtered out of the signal prior to application of the detection methods.

Near term plans include instrumenting two spur gear fatigue test rigs at NASA Lewis with an on-line system capable of independently applying various diagnostic techniques. This will provide an excellent means of verifying and linking certain parameters with specific gear faults.

3 CONCLUDING REMARKS

This paper reviewed recent analytical activities at NASA Lewis in the areas of gear noise, vibration, and diagnostics performed in-house and through NASA and U.S. Army sponsored grants and contracts. These research efforts are summarized below.

3.1 Gear tooth profile research

Two research activities at NASA Lewis have focused on ways to reduce the transmission error through gear tooth profile modification studies. The first study examined the effects of gear tooth crowning to reduce transmission error due to gear misalignments. The second study analyzed the effects of a number of different linear and parabolic tooth profile modi-

fications on the transmission error and dynamic load of a set of spur gears.

3.2 Gear train dynamics research

Several dynamic gear system programs have been developed and refined at NASA Lewis to provide an understanding of the dynamic relationships between the various components in a transmission system. An existing one stage epicyclic gear dynamics program was expanded to a two stage program with optional peripheral components. Another effort resulted in the development of a finite element model of a geared rotor system with flexible bearings.

3.3 Gear housing dynamics, transmissibility, and acoustics research

Several research activities at NASA Lewis have focused on modeling the dynamics, transmissibilities, and acoustics of a simple gearbox housing. This is part of an overall program to develop the technology to reduce the structurally transmitted gear-induced vibration in rotorcraft. One study analyzed the dynamics of the gear housing from the gear noise test rig using finite element analysis and experimental modal analysis. Further work concentrated on the complex transmission of vibration through rolling element bearings, which resulted in a new bearing model being developed. In another effort a computer program was developed that simulates the overall dynamics of a multimesh multistage geared rotor bearing system with housing vibration coupling effects. Finally, some preliminary gearbox acoustic radiation predictions were made using a boundary element program.

3.4 Gear diagnostics research

A research program to study new and existing techniques in gear train diagnostics was recently initiated at NASA Lewis. The first phase of this program involved investigating and applying current gear failure prediction techniques to experimental data from a gear fatigue test rig.

The research efforts reviewed in this paper are focused at developing the advanced technology required in the areas of gear noise vibration and diagnostics for future military and civilian rotorcraft. The unique experimental facilities available at NASA Lewis are being used to validate and refine these analytical activities. Combined, these analytical and experimental efforts in the areas of gear noise, vibration, and diagnostic research will produce design tools for developing the more powerful, lighter, and quieter next generation rotorcraft.

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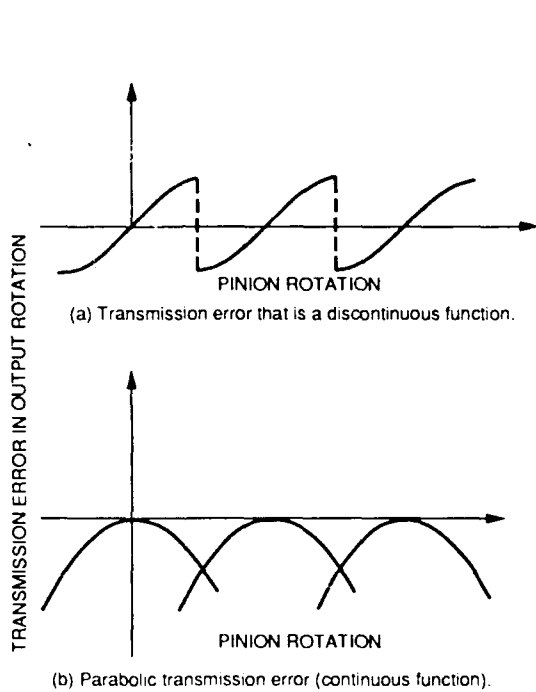


Figure 1. - Output transmission error as a function of input gear rotation.

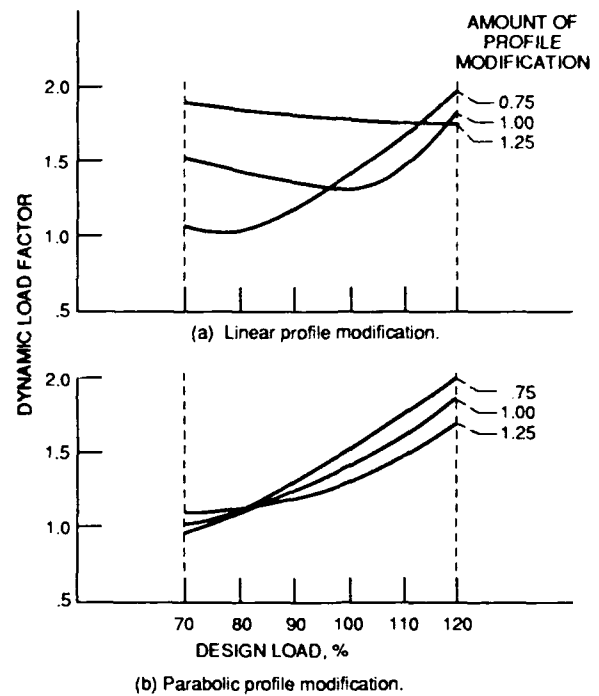


Figure 2. - Comparison of linear and parabolic profile modification as a function of load and modification magnitude.

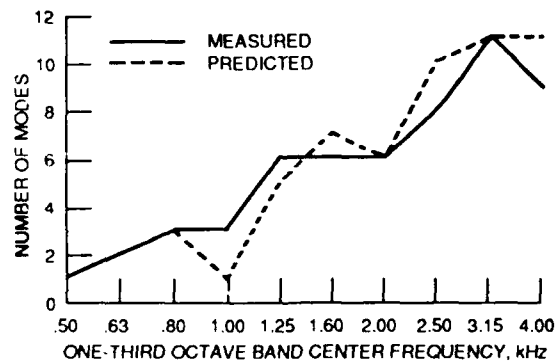


Figure 3. - Comparison of experimental data and analytical prediction of gear noise rig housing dynamics.

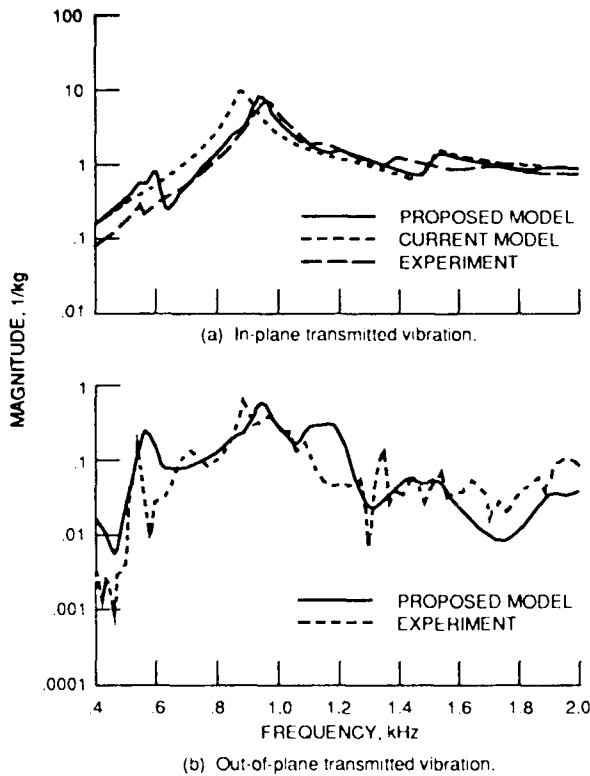


Figure 4. - Comparison of proposed bearing model, current model, and experimental data on in-plane and out-of-plane transmitted vibration.

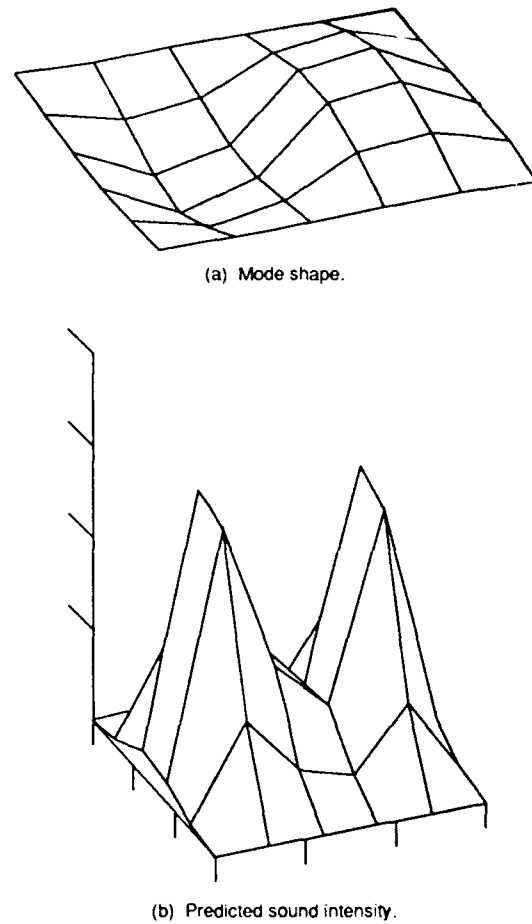


Figure 5. - Comparison of mode shape and predicted sound intensity for 1290 Hz vibration mode on the top surface of the gear noise rig housing

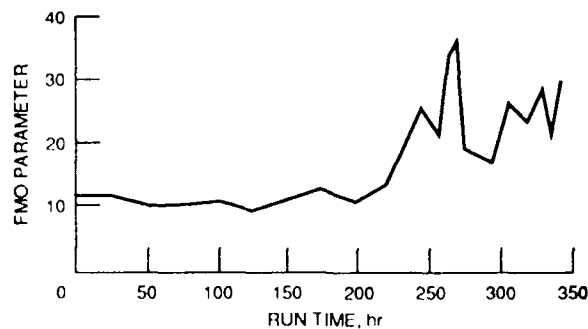


Figure 6. - Plot of FMO parameter as a function of run time for a gear mesh experiencing failure by heavy wear.